

## **OPTICAL ROUTER**

### **CROSS-REFERENCE TO RELATED APPLICATIONS**

Related subject matter is disclosed in co-pending, commonly assigned,  
5 U.S. Patent application Serial Number 09/430318, filed on October 29, 1999.

### **FIELD OF THE INVENTION**

The present invention relates to communications, generally, and more particularly to an optical router well suited for Internet Protocol ("IP") traffic.

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### **BACKGROUND OF THE INVENTION**

The rapid growth of Internet traffic has created an increasing need for more responsive inter-networking components. One component approaching its operative limits is the IP router. IP routers route packets of data traffic between 15 destinations in an inter-network.

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Presently, IP routers are electronic switch based devices. To date, electronic switch based IP routers having 16 input and 16 output channels are commercially available. Extending the number of input and output channels, however, has raised substantial challenges due to the space management issues, power and heat dissipation, as well as electromagnetic interference. It is believed 20 that given their limited number of input and output channels, electronic switch based IP routers may very shortly reach their capacity to route inter-network traffic. As a result, optically based components, including IP routers, are being explored by industry. It is estimated that optical IP routers may soon be realized 25 having 128 input and 128 output channels, and thus, greater overall throughput.

In view of the above, a demand exists for an optical IP router offering an increased number of input and output channels, and greater overall throughput.

### **SUMMARY OF THE INVENTION**

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In co-pending, commonly assigned, U.S. Patent application of Brinkman et al., Serial Number 09/430,318, filed on October 29, 1999, an optical router is described for routing signals by determining an intended destination for a packet

to be routed, appropriately “coloring” the packet according to a selected wavelength in a destination-specific manner, and then transmitting the colored packet through an optical frequency router. By this arrangement, the colored packet of data is routed to a desired destination.

5        We have invented an optical router having increased throughput over the hereinabove referenced U.S. patent application. Our optical router employs an optical frequency router for simultaneously receiving at least two signals which are differently “colored” – having different wavelengths - in one input port. The optical frequency router also simultaneously presents at least two routed signals  
10      which are differently “colored” – having different wavelengths - at one output port. By this arrangement, a number of colored packets of data may be simultaneously routed to each of their desired destinations through one port.

15      In an illustrative embodiment of the present invention, an optical router is disclosed. The optical router comprises a plurality of combiners, a plurality of receivers, and at least one optical frequency router for routing optical signals by their color. To increase the number of input and output channels of the optical router, at least one input port of the frequency router is coupled with one combiner for combining optical signals of different colors, while at least one output port of the optical frequency router is coupled with one receiver for separating and directing at least two frequency routed optical signals to their intended destinations.  
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These and other embodiments, advantages and objects will become apparent to skilled artisans from the following detailed description read in conjunction with the appended claims and the drawings attached hereto.

25      **BRIEF DESCRIPTION OF THE DRAWINGS**

The present invention will be better understood from reading the following description of non-limiting embodiments, with reference to the attached drawings, wherein below:

30      **FIG. 1** illustrates a first embodiment of the present invention;

**FIG. 2** illustrates a second embodiment of the present invention;

**FIG. 3** illustrates a third embodiment of the present invention;

**FIG. 4** illustrates a fourth embodiment of the present invention;

**FIG. 5** illustrates a fifth embodiment of the present invention;

**FIG. 6** illustrates a sixth embodiment of the present invention;

5      **FIG. 7** illustrates a converter according to an embodiment of the present invention; and

**FIG. 8** illustrates an optical frequency router device according to an embodiment of the present invention.

It should be emphasized that the drawings of the instant application are not to scale but are merely schematic representations, and thus are not intended  
10      to portray the specific parameters or the structural details of the invention, which can be determined by one skilled in the art by examination of the information herein.

#### **DETAILED DESCRIPTION OF THE PRESENT INVENTION**

Referring to **FIG. 1**, an optical router **10** is illustrated according to a first embodiment of the present invention. Optical router **10** routes signals from a plurality of router input channels, **12**, **14**, **16** and **18**, to a plurality of router output channels, **38**, **40**, **42** and **44**. Router input channels, **12**, **14**, **16** and **18** each receive a signal to be routed. In an embodiment of the present invention, each signal to be routed is a packet of data employing an Internet Protocol (“IP”) format, for example - other formats and standards, however, may also be used.  
15      Each IP packet of data has its intended destination residing therein, as will be better understood from the disclosure hereinbelow in association with **FIG. 7**.

Optical router **10** comprises an optical frequency router **20**. Optical frequency router **20** routes optical signals in response to their wavelength or color, as will be better understood from the disclosure hereinbelow in association  
25      with **FIG. 8**. Frequency router **20** has a plurality of input ports, **22** and **24**, and a plurality of output ports, **26** and **28**.

Optical router **10** also comprises a pair of input devices, **30** and **32**. Input devices, **30** and **32**, convert received packets of data into corresponding optical signals. Each optical signal, as converted, is “colored” in response to the intended destination information of the respective packet of data. The resultant optical  
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signal, as colored, has a wavelength corresponding with an intended output port, **26** or **28**, to which it is to be routed to by frequency router **20**.

Each input port, **22** and **24**, of frequency router **20** is respectively coupled with an input device, **30** and **32**. Likewise, each input device, **30** and **32**, is coupled with a group of router input channels, **12** and **14**, and, **16** and **18**, respectively. Each input device, **30** and **32**, may simultaneously receive more than one incoming packet of data from its respective router input channels. Consequently, each input device, **30** and **32**, may combine more than one optical signal if they are of different wavelengths or colors.

10 Optical router **10** comprises a centralized scheduler (not shown) for scheduling the conversion of each received packet of data into an optical signal. The scheduler enables the coloring of each optical signal in response to the intended destination information of the corresponding packet of data, to avert overlap of optical signals having the same color, also referred to as collisions. In scheduling the conversion of packets of data, the scheduler may delay one packet of data relative to another if both are to be routed to the identical router output channel. Likewise, the scheduler may delay one packet relative to another if both are received by the same input device and are to be routed through the same output port of frequency router **20** to different destinations.

15 In the illustrative embodiment, a number of packets of data, **1a** and **2a**, are simultaneously received by input device **30**, while a packet of data **2b** is received by input device **32**. Each respective input device, **30** and **32**, converts these packets of data into corresponding optical signals,  $\lambda_{1a}$ ,  $\lambda_{2a}$  and  $\lambda_{2b}$  - each of which are colored in response to their destination. Input device **30**, receiving packets of data, **1a** and **2a**, combines the converted optical signals,  $\lambda_{1a}$  and  $\lambda_{2a}$ , into a combined optical signal having two component signals. As a result, input port **22** simultaneously receives the combined optical signal. Likewise, input port **24** receives the converted optical signal  $\lambda_{2b}$ . Given its physical properties, frequency router **20** routes optical signals  $\lambda_{1a}$  and  $\lambda_{2a}$  from input port **22** to outputs ports **26** and **28**, respectively, and optical signal  $\lambda_{2b}$  from input port **24** to output port **26**.

Coupled with each output port, **26** and **28**, is a receiver, **34** and **36**. Each receiver, **34** and **36**, is also coupled with a group of router output channels, **38** and **40**, and, **42** and **44**, respectively. Each receiver, **34** and **36**, is capable of separating routed optical signal components combined by frequency router **20** at its respective output port. Each receiver, **34** and **36**, also presents - or, in other words, directs - each routed optical signal component to its respective intended destination. In the illustrative embodiment, receiver **34** simultaneously receives optical signals,  $\lambda_{1a}$  and  $\lambda_{2b}$ , from output port **26**, while receiver **36** receives optical signal  $\lambda_{2a}$  from output port **28**. Consequently, receiver **34** presents optical signals,  $\lambda_{1a}$  and  $\lambda_{2b}$ , to router output channels **38** and **40**, respectively, and receiver **36** presents optical signals,  $\lambda_{2a}$ , to router output channel **42**. Moreover, each receiver, **34** and **36**, also converts each received optical signal,  $\lambda_{1a}$ ,  $\lambda_{2a}$  and  $\lambda_{2b}$ , back into packets of data, **1a**, **2a**, and **2b**, in the electrical domain.

Frequency router **20** comprises  $N$  input ports and  $N$  output ports, where  $N$  is equal to two (2) in the illustrative embodiment. Each input port of frequency router **20** is also capable of simultaneously receiving,  $N$ , or two (2) optical signals from a respective input device, while each output port is capable of simultaneously presenting,  $N$ , or two (2), optical signals to a respective receiver. Consequently, optical router **10** has  $NxN$  router input channels and  $NxN$  router output channels.

Referring to FIG. 2, an optical router **50** is illustrated according to a second embodiment of the present invention. While employing the same operational principles as optical router **10** of FIG. 1, the architecture of optical router **50** supports greater than  $NxN$  router input channels and  $NxN$  router output channels. Optical router **50** comprises an optical frequency router **80** having  $N$  input ports, **68**, **70** and **72**, and  $N$  output ports, **74**, **76** and **78**, where  $N$  is equal to three (3).

In the illustrative embodiment, input port **68** is capable of simultaneously receiving  $M$ , or five (5), optical signals from an input device **62** through router input channels **52**, **54**, **56**, **58** and **60**. Likewise, output port **74** is capable of simultaneously presenting  $M$ , or five (5), optical signals to a receiver **82**, and,

thus, router output channels **88**, **90**, **92**, **94** and **96**. If the number of optical signals received by an input port exceeds the number of output ports, frequency router **80** routes two or more of these optical signals to the same output port. A data collision, however, may be avoided if these routed signals have different colors (wavelengths) and the ratio of their wavelengths satisfies the modal properties of frequency router **80**, as will be better understood from the disclosure hereinbelow in association with **FIG. 8**.

It should be apparent to skilled artisans from the hereinabove disclosure that input ports **70** and **72** may each also simultaneously receive **M** optical signals through input devices, **64** and **66**, respectively, while output ports **76** and **78** may each also simultaneously present to their respective receivers, **84** and **86**, **M** optical signals. Here, optical router **50** will have **NxM** router input channels and **NxM** router output channels. To effectively increase the number of input and output channels of optical router **50** with respect to optical router **10** of **FIG. 1**, **M** should be greater than **N**. The maximum number of input and output channels available to optical router **50** is primarily limited by the material properties of frequency router **80**.

Referring to **FIG. 3**, an optical IP router **100** is illustrated according to a third embodiment of the present invention. Optical IP router **100** routes signals from a number of router input channels, **102<sub>1</sub>-102<sub>M</sub>**, **104<sub>1</sub>-104<sub>M</sub>**, and **106<sub>1</sub>-106<sub>M</sub>**, to a number of router output channels, **164<sub>1</sub>-164<sub>M</sub>**, **166<sub>1</sub>-166<sub>M</sub>**, and **168<sub>1</sub>-168<sub>M</sub>**. Router input channels, **102<sub>1</sub>-102<sub>M</sub>**, **104<sub>1</sub>-104<sub>M</sub>**, and **106<sub>1</sub>-106<sub>M</sub>**, each may receive an IP packet of data having its intended destination residing therein.

Optical router **100** comprises an optical frequency router **120** for routing optical signals in response to their wavelength or color. Optical router **100** also comprises a plurality of input devices, **110<sub>1</sub>-110<sub>N</sub>**. Each input device converts a number of received IP packets of data from a corresponding number of router input channels into a number of colored optical signals. Each optical signal, as converted, may be "colored" in response to the intended destination information of the respective packet of data.

To effectively convert each received IP packet of data, each input device comprises a number of converters, **112<sub>1</sub>-112<sub>M</sub>**, **114<sub>1</sub>-114<sub>M</sub>** and **116<sub>1</sub>-116<sub>M</sub>**, each

corresponding with a router input channel, **102<sub>1</sub>-102<sub>M</sub>**, **104<sub>1</sub>-104<sub>M</sub>**, and **106<sub>1</sub>-106<sub>M</sub>**. Each converter comprises a tunable laser ("TL") for generating a carrier monochromatic light beam having a particular wavelength or color selected in response to a received packet of data and controlled by a centralized scheduler 5 **135**, as will be better understood from the disclosure hereinbelow in association with FIG. 7. The carrier light beam is subsequently modulated by a modulator in response the received packet of data, resulting in an optical data signal having a color corresponding with the intended destination of received packet of data.

Each input device, **110<sub>1</sub>-110<sub>N</sub>**, also comprises an optical power combiner, 10 **118<sub>1</sub>-118<sub>N</sub>**. Each combiner, **118<sub>1</sub>-118<sub>N</sub>**, is coupled with a number of corresponding converters, **112<sub>1</sub>-112<sub>M</sub>**, **114<sub>1</sub>-114<sub>M</sub>** and **116<sub>1</sub>-116<sub>M</sub>**, associated with a respective input device; **110<sub>1</sub>-110<sub>N</sub>**. Each combiner combines simultaneously received optical signals, as colored. Consequently, a plurality of combined optical signals, **125<sub>1</sub>-125<sub>N</sub>**, are output from each corresponding input device. It should 15 be noted that scheduler **135** prevents each combiner from combining more than one optical signal of the same color.

Frequency router **120** comprises a plurality of input ports, **130<sub>1</sub>-130<sub>N</sub>**, and a plurality of output ports, **140<sub>1</sub>-140<sub>N</sub>**. Coupled with an input device, each input port may receive a combined optical signal. Frequency router **120** routes 20 each component optical signal within a combined optical signal to an output port in response to the color of the respective signal. Thus, for example, if combined optical signal, **125<sub>1</sub>**, comprising component optical signals from converted packets of data of each router input channel, **102<sub>1</sub>-102<sub>M</sub>**, is received by input port **130<sub>1</sub>**, frequency router **120** routes each component optical signal to one 25 output port. If input ports **130<sub>2</sub>-130<sub>N</sub>** also receive combined optical signals, a number of routed optical signals may also be simultaneously presented to a number of output ports. Given the characteristics of frequency router **120**, the routed optical signals presented at an exemplary output port, **140<sub>1</sub>**, will have 30 different colors. Therefore, each output port may present a resultant optical signal, **145<sub>1</sub>-145<sub>N</sub>**, comprising a number of component routed optical signals therein.

IP router **100** also comprises a plurality of output receivers, **150<sub>1</sub>-150<sub>N</sub>**. Each receiver is coupled with an output port of frequency router **120** for receiving a resultant optical signal, **145<sub>1</sub>-145<sub>N</sub>**. Each receiver, **150<sub>1</sub>-150<sub>N</sub>**, comprises an optical power splitter, **152<sub>1</sub>-152<sub>N</sub>**. Each splitter, **152<sub>1</sub>-152<sub>N</sub>**, is 5 coupled with a number of corresponding tunable filters ("TF"), **154<sub>1</sub>-154<sub>M</sub>**, **156<sub>1</sub>-156<sub>M</sub>** and **160<sub>1</sub>-160<sub>M</sub>**, associated with a respective receiver, **150<sub>1</sub>-150<sub>N</sub>**. Each splitter splits or divides the optical power of a corresponding resultant optical signal, **145<sub>1</sub>-145<sub>N</sub>**, amongst its respective tunable filters.

By this arrangement, each tunable filter may receive a power divided 10 representation of a resultant optical signal, **145<sub>1</sub>-145<sub>N</sub>**. At least one tunable filter of the corresponding receiver is tuned to the color of a component optical signal of the resultant optical signal, through scheduler **135**, in response to the intended destination of an original packet of data. The tuning of the tunable filter enables each component optical signal within a resultant optical signal to pass to its 15 intended destination.

It should be noted that optical IP router **100** prevents the simultaneously routing of more than one IP packet of data received by one input device, **110<sub>1</sub>-110<sub>N</sub>**, to one output receiver, **150<sub>1</sub>-150<sub>N</sub>**. This limitation is based on the fact that both IP packets of data would require the same coloring to be routed to the same 20 output receiver. To avert a data collision, in one embodiment, scheduler **135** introduces a delay between such IP packets of data. However, this potential limitation also enables optical IP router **100** to route one packet of data from one router input channel associated with one input device to any number of router output channels associated with one output receiver by setting some or all of the 25 corresponding tunable filters to the same color. This routing feature, also referred to as partial multicasting, allows optical IP router **100** to route, for example, one packet of data from router input channel **102<sub>2</sub>** to router output channels **166<sub>1</sub>-166<sub>M</sub>**.

Referring to FIG. 4, an optical IP router **200** is illustrated according to a 30 fourth embodiment of the present invention. Optical router **200** operates similarly to optical IP router **100** of FIG. 3. However, optical router **200**

employs a two stage routing architecture to replace tunable filters, **154<sub>1</sub>-154M**, **156<sub>1</sub>-156M** and **160<sub>1</sub>-160M**.

The two stage architecture of optical router **200** comprises a first and a second stage optical frequency router, **220** and **260**, for routing packets of data from a number of router input channels, **202<sub>1</sub>-202M**, **204<sub>1</sub>-204M**, and **206<sub>1</sub>-206M**, to a number of router output channels, **280<sub>1</sub>-280M**, **282<sub>1</sub>-282M**, and **284<sub>1</sub>-284M**. Optical router **200** comprises a plurality of first stage input devices, **210<sub>1</sub>-210N**. Each input device, **210<sub>1</sub>-210N**, much like the input devices, **110<sub>1</sub>-110N**, of FIG. 3, comprises a number of converters, **212<sub>1</sub>-212M**, **214<sub>1</sub>-214M**, and **216<sub>1</sub>-216M**. Each converter comprises a tunable laser ("TL") for converting a received IP packet of data into an optical signal colored in response to its intended destination. Each input device also comprises a combiner, **218<sub>1</sub>-218N**, for combining the colored optical signals into a combined optical signal of a number of colors, and a scheduler **235** for preventing more than one optical signal of the same color from being combined. A combined optical signal, **222<sub>1</sub>-222N**, may be generated by each corresponding input device.

First stage frequency router **220** comprises a plurality of input ports, **225<sub>1</sub>-225N**, and a plurality of output ports, **230<sub>1</sub>-230N**. Each input port is associated with one input device to receive one combined optical signal, **222<sub>1</sub>-222N**. First stage frequency router **220** routes each optical signal component within a combined optical signal to an output port in response to its color. As such, each output port may have a resultant optical signal, **238<sub>1</sub>-238N**, comprising a number of simultaneously presented routed optical signals each having a different color.

Optical router **200** also comprises a plurality of second stage input devices, **240<sub>1</sub>-240N**, each for coupling an output port of first stage frequency router **220** with an input port, **255<sub>1</sub>-255N**, of second stage frequency router **260**. Each second stage input device, **240<sub>1</sub>-240N**, comprises a second stage demultiplexer, **242<sub>1</sub>-242N**, for demultiplexing a resultant optical signal, **238<sub>1</sub>-238N**, into a number of component, once routed, optical signals. Each second stage input device also comprises a number of second stage converters, **244<sub>1</sub>-244M**, **246<sub>1</sub>-246M**, and **248<sub>1</sub>-248M**, and a second stage combiner, **250<sub>1</sub>-250N**,

resulting in combined second stage optical signals,  $252_1\text{-}252_N$ . By this arrangement, each once routed optical signal component is directed to a specific second stage converter in response to its color. Each second stage converter, in response to the intended destination of the original packet of data, re-colors the  
5 received once routed optical signal component, to form a second stage optical signal.

It should be noted that each second stage converter converts a received demultiplexed routed optical signal into an electrical signal. Each second stage converter recreates the once routed optical signal component as a second stage  
10 optical signal from the electrical representation created. In response to the intended destination of the original received packet of data, the second stage optical signal is colored, as controlled by scheduler **235**.

Scheduler **235** may be realized using a centralized design. Alternatively,  
15 scheduler **235** may comprise a number of independent schedulers. Here, each input device,  $210_1\text{-}210_N$ , and each second stage input device,  $240_1\text{-}240_N$ , has an associated independent scheduler. Each independent scheduler controls the routing of packets of data corresponding with its associated input device. As a consequence, each independent scheduler need not interact with any other independent scheduler, thereby simplifying the scheduling computations  
20 associated with a centralized scheme.

Each input port,  $255_1\text{-}255_N$ , may receive one combined second stage optical signal,  $252_1\text{-}252_N$ . Second stage frequency router **260** routes each component of the combined second stage optical signals,  $252_1\text{-}252_N$ , as received by an associated input port, according to their color. As such, each second stage  
25 routed optical signal,  $268_1\text{-}268_N$ , comprises routed components of different second stage optical signals,  $252_1\text{-}252_N$ . The resultant routed optical signals,  $268_1\text{-}268_N$ , are presented by each output port,  $265_1\text{-}265_N$ , to a corresponding output stage receiver,  $270_1\text{-}270_N$ .

Each output stage receiver,  $270_1\text{-}270_N$ , comprises an output stage  
30 demultiplexer,  $272_1\text{-}272_N$ , for demultiplexing one resultant routed optical signal,  $268_1\text{-}268_N$ . Each resultant routed optical signal,  $268_1\text{-}268_N$ , may have a number of component optical signals therein. As such, each component of the

resultant routed optical signals is directed to a particular router output channel, **280<sub>1</sub>-280<sub>M</sub>**, **282<sub>1</sub>-282<sub>M</sub>**, and **284<sub>1</sub>-284<sub>M</sub>**, and thus, presented to the intended destination of the original packet of data.

Referring to FIG. 5, an optical IP router **300** is illustrated according to a fifth embodiment of the present invention. Optical router **300** operates similarly to optical IP router **200** of FIG. 4. However, optical router **300** enables one packet of data received by any one router input channel to be simultaneously routed to any number of router output broadcasting channels. This feature is defined as full multicasting or router broadcasting.

To realize this full multicasting feature, optical router **300** comprises a first and a second stage optical frequency router, **320** and **370**, for routing packets of data, between a number of router input channels, **302<sub>1</sub>-302<sub>N</sub>**, **304<sub>1</sub>-304<sub>N</sub>**, and **306<sub>1</sub>-306<sub>N</sub>**, and a number of router output channels, **396<sub>1</sub>-396<sub>M</sub>**, **398<sub>1</sub>-398<sub>M</sub>**, and **400<sub>1</sub>-400<sub>M</sub>**. Optical router **300** comprises a plurality of first stage input devices, **310<sub>1</sub>-310<sub>N</sub>**. Each input device, **310<sub>1</sub>-310<sub>N</sub>**, comprises a number of fixed lasers ("FL"), **312<sub>1</sub>-312<sub>M</sub>**, **314<sub>1</sub>-314<sub>M</sub>**, and **316<sub>1</sub>-316<sub>M</sub>**, for converting a received IP packet of data into an optical signal.

Unlike the previous embodiments, each optical signal may be colored in response to which fixed laser, and thus which router input channel, receives the IP packet of data. For example, each packet of data received by router input channel, **302<sub>2</sub>**, and fixed laser **312<sub>1</sub>**, should be similarly colored. Each input device, **310<sub>1</sub>-310<sub>N</sub>**, also comprises a multiplexer, **318<sub>1</sub>-318<sub>N</sub>**, for multiplexing, or in other words, combining each of the optical signals received from the corresponding fixed lasers, and for generating a multiplexed or combined optical signal, **322<sub>1</sub>-322<sub>N</sub>**.

First stage frequency router, **320**, comprises a plurality of input ports, **325<sub>1</sub>-325<sub>N</sub>**, each for receiving a multiplexed optical signal, **322<sub>1</sub>-322<sub>N</sub>**, from an input device. Frequency router, **320**, routes each component optical signal of the received multiplexed signals, **322<sub>1</sub>-322<sub>N</sub>**, according to its color. Frequency router, **320**, at each output port, **325<sub>1</sub>-325<sub>N</sub>**, presents a resultant routed optical signal, **338<sub>1</sub>-338<sub>N</sub>**, each of which may comprise routed components of other multiplexed signals, **322<sub>1</sub>-322<sub>N</sub>**.

Each output port,  $330_1$ - $330_N$ , is coupled with a second stage receiver,  $340_1$ - $340_N$ . Each second stage receiver comprises an optical power splitter,  $342_1$ - $342_N$ , for splitting one received resultant routed optical signal from the corresponding output port amongst a number of tunable filters ("TF"),  $344_1$ -  
5  $344_M$ ,  $348_1$ - $348_M$ , and  $352_1$ - $352_M$ . Each tunable filter receives a power divided representation of a resultant routed optical signal,  $338_1$ - $338_N$ , and may be tuned to the color of a component optical signal in response to the intended destination of an original packet of data by a centralized scheduler  $335$ . Each tunable filter may pass a component optical signal from resultant routed optical signal,  $338_1$ -  
10  $338_N$ , to a corresponding fixed laser,  $346_1$ - $346_M$ ,  $350_1$ - $350_M$ ,  $354_1$ - $354_M$ . Each fixed laser converts or re-colors a component optical signal, as passed by a corresponding tuned filer. Here, the resultant optical signal may be colored according to which fixed laser receives the component optical signal. For example, each component optical signal passed by tunable filter  $344_2$  to fixed  
15 laser  $346_2$  will be colored identically.

Each output device,  $340_1$ - $340_N$ , also comprises a multiplexer,  $356_1$ - $356_N$ , for multiplexing each of the optical signals received from the corresponding second stage fixed lasers, and for generating a second stage multiplexed optical signal,  $358_1$ - $358_N$ . Further, each second stage multiplexed optical signal is received by one input port,  $365_1$ - $365_N$ , of second stage frequency router,  $370$ . Frequency router,  $370$ , routes each component optical signal of the received second stage multiplexed signals,  $358_1$ - $358_N$ , according to its color. Frequency router,  $370$ , at each output port,  $375_1$ - $375_N$ , presents a final stage optical signal,  $378_1$ - $378_N$ . Each final stage optical signal may comprise routed components from other second stage multiplexed signals,  $358_1$ - $358_N$ .

Each output port,  $375_1$ - $375_N$ , is coupled with an output stage receiver,  $380_1$ - $380_N$ . Each output stage receiver comprises a power splitter,  $382_1$ - $382_N$ , for splitting a final stage optical signal,  $378_1$ - $378_N$ , as received from the corresponding output port, amongst a number of associated output stage tunable filters,  $384_1$ - $384_M$ ,  $388_1$ - $388_M$ , and  $392_1$ - $392_M$ . Each tunable filter receives a power divided representation of a final stage optical signal,  $378_1$ - $378_N$ . One or more tunable filters may be tuned to the color of a component optical signal,

through a scheduler 335, in response to the intended destination of an original packet of data. Consequently, the passed optical signal may be effectively routed to its intended destination via router output channels, 396<sub>1</sub>-396<sub>M</sub>, 398<sub>1</sub>-398<sub>M</sub>, and 400<sub>1</sub>-400<sub>M</sub>.

5 Referring to FIG. 6, an optical IP router 450 is illustrated according to a sixth embodiment of the present invention. Optical IP router 450 is an alternative configuration of optical IP router 200 of FIG. 4, employing one optical frequency router 480. It should be noted that optical IP router 300 of FIG. 5 may also be modified in accordance with the configuration of optical IP  
10 router 450.

Frequency router 480 comprises a number of ports, 475<sub>1</sub>-475<sub>N</sub> and 485<sub>1</sub>-  
15 485<sub>N</sub>, each of which function in a dual role: (1) for receiving combined optical signals from a number of tunable lasers; and (2) for presenting a routed optical signal comprising a number of differently colored optical signals. Moreover,  
20 frequency router 480 employs a number of circulators, 465<sub>1</sub>-465<sub>N</sub> and 470<sub>1</sub>-  
470<sub>N</sub>, each of which coupled with one port. Known to skilled artisans, optical circulators functionally separate optical signals propagating in different directions. Each circulator enables a combined optical signal and a routed optical signal having various component signals to propagate through the same port, unobstructed.

For example, a packet of data is received by a converter, 455<sub>1</sub>, to produce an optical signal, 458<sub>1</sub>, colored in response to its destination. Optical signal, 458<sub>1</sub>, is received by combiner 460<sub>2</sub>, where it may be combined with other optical signals, resulting in a combined optical signal 462<sub>2</sub>. Circulator 465<sub>2</sub> allows  
25 combined optical signal 462<sub>2</sub> to propagate to port 475<sub>2</sub>, while a routed optical signal, 468<sub>2</sub>, is presented to circulator 465<sub>2</sub> from port 475<sub>2</sub>. Routed optical signal, 468<sub>2</sub>, is directed by circulator 465<sub>2</sub> to a demultiplexer, 490<sub>2</sub>, for example, and directed to a number of light detecting devices, including device 495<sub>2</sub>.

30 Referring to FIG. 7, a converter 500 is illustrated as may employed in the present invention. Converter 500 receives packets of data, each of which may employ an Internet Protocol (“IP”) format. Each IP packet of data comprises a

header containing source and destination identifiers, as well as a data portion. The source identifier identifies the source or origin of the packet of data, while the destination identifies the intended destination of the specific packet. The data portion of the packet contains the data to be conveyed from the source to the  
5 destination. Using converter **500**, each packet of data may be "colored" according to its destination. More specifically, an appropriate wavelength or color of light is selected for each packet of data to enable its transport through an optical frequency router to a desired output port.

Converter **500** comprises a tunable transmitter **515** and a modulator **520**.  
10 Tunable transmitter **515** may be realized by various components including a tunable laser. Upon determining the destination of each packet of data and selecting an appropriate color, tunable transmitter **515** is tuned to the appropriate color and the packet of data may be modulated by modulator **520** into an optical packet signal of the designated appropriate color. The resultant  
15 colored optical packet of data is thereafter output to a combiner, as detailed hereinabove.

The selection of an appropriate color for each packet of data in view of its destination is controlled by central scheduler **525**. Central scheduler **525** protects against data collisions if two packets of data within two converters of an  
20 input device, **110<sub>1</sub>**, of FIG. 3, for example, have the same destination. In such circumstances, one packet of data may be delayed by a memory device, such as a buffer **510**, before being colored.

In another embodiment of the present invention, converter **500** comprises a light detector **505**, such as a photodiode, for converting an optical  
25 packet of data into an electrical representation. The resultant electrical signal may be fed into a buffer **510** for temporary storage. Buffer **510** relays the electrical signal to modulator **520**, in response to scheduler **525**, to enable the carrier light beam from laser **515** to be modulated.

Referring to FIG. 8, an optical frequency router **600** is illustrated as  
30 employed in the present invention. Optical frequency router **600** is a class of electro-optical components proposed for routing optical signals. Various realizations are available presently, including a Waveguide Grating Router

(“WGR”), as is disclosed in United States Patent Numbers 5,002,350 and 5,136,671, and hereby incorporated by reference.

Frequency router **600** comprises an interconnecting apparatus having a plurality of input ports, **605<sub>1</sub>-605<sub>N</sub>**, each of which are connected to a free space region **610**. Frequency router **600** further comprises a plurality of output waveguides **620** extending from free space region **610**. Each output waveguide **620** of the plurality is coupled with an optical grating **630**. Optical grating **630** comprises a plurality of unequal length waveguides. The differing lengths of these waveguides cause distinct relative phase delays between optical signals propagating through optical grating **630**. Each waveguide of the plurality of unequal length waveguides is coupled with an input waveguide of a plurality of input waveguide **640**. Each input waveguide is connected to a second free space region **650**. Extending from second free space region **650** is a plurality of output ports, **655<sub>1</sub>-655<sub>N</sub>**. Typically, input and output ports, **605<sub>1</sub>-605<sub>N</sub>** and **655<sub>1</sub>-655<sub>N</sub>**, are respectively formed from waveguides.

It should be apparent to skilled artisans that frequency router **600** may operate as a multiplexer and/or a demultiplexer of optical frequencies. Thus, if an optical signal having an amplitude A is received by input port **605<sub>1</sub>**, a number of optical signals are produced at the output ports **655<sub>1</sub>-655<sub>N</sub>**. The optical signals at the output ports **655<sub>1</sub>-655<sub>N</sub>** have corresponding amplitudes of  $AT_1$ ,  $AT_2$ ,  $AT_N$ , where  $T_i$  is the value of the transmission coefficient for input port **605<sub>1</sub>** and each output port **655<sub>1</sub>-655<sub>N</sub>**. Furthermore, from these properties, frequency router **600** may direct an optical signal received by an input port, **605<sub>1</sub>-605<sub>N</sub>**, into an output port, **655<sub>1</sub>-655<sub>N</sub>**, in response to its wavelength or color.

While the particular invention has been described with reference to illustrative embodiments, this description is not meant to be construed in a limiting sense. It is understood that although the present invention has been described, various modifications of the illustrative embodiments, as well as additional embodiments of the invention, will be apparent to skilled artisans upon reference to this description without departing from the spirit of the invention, as recited in the claims appended hereto. It is therefore contemplated

that the appended claims will cover any such modifications or embodiments as fall within the true scope of the invention.